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Research Article

Lowering Emissivity of Concrete Roof Tile's Underside Cuts Down Heat Entry to the Building

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Buildings in Southern China widely use a double-skin roof to reduce heat entry through the roof to the building interior during summertime. Concrete roof tiles are preferably installed as the outmost layer of the double-skin roof due to their resistance to hail and wind damages and their attractive price. However, after construction, the tile's top tends to be darkened by dust deposit and algae growth, increasing the heat entry through the roof to the building. Here, we show that this heat entry can be curtailed by lowering the emissivity at the tile's underside. Temperatures and heat fluxes at different elevations of a double-skin roof with concrete tiles as the outmost layer of the roof are monitored. The underside of each concrete tile is coated with a specific paint to get a unique emissivity. Observations reveal that lowering the emissivity of concrete roof tiles could cut down the summer heat gain of buildings in tropical regions.

1. Introduction

A double-skin roof is composed of a pair of parallel sheets intermediate by an air layer [1]. The outmost sheet of the roof shields the sunlight from the roof deck and thus reduces heat entry through the roof to the building due to the heat loss in the heat transfer caused by the air layer [2, 3]. In Southern China, concrete tiles are typically constructed as the outmost sheet of a double-skin roof due to their resistance to wind and hail damages, their attractive price, and the easy installation. Zingre et al. [4] found that such a roof can reduce 6% of the annual heat entry through the building roof during the daytime, but it also impedes the heat loss at nighttime. Tong et al. [5] investigated the heat entry to the building interior through double-skin tile roofs with different albedos and found that the heat entry to the building interior can be cut about 11% if the rooftop albedo reduces a unit of 0.10. In addition, the heat transfer through a double-skin facade has been investigated widely in the aspects of configuration optimum [6], ventilation characteristics [7], façade's strikes [8], and facade's albedos [9]. In addition, the type, usage, orientation, and insulation of a building greatly influence the energy efficiency of a double-skin façade.

Heat entry through the concrete roof tile to the building interior primarily depends on the heat transfers in the tile and in the air gap under the tile. Raising the albedo of the tile's top (rooftop) reflects more sunlight off the tile and thus lowers down heat entry through the roof to the inner building. However, in Southern China, after the installation of roof tiles for several years, the top of concrete tiles is darkened by dust deposit and algae growth (Figure 1). As the height of the air layer under the tile is several orders of the magnitude lower than the width and length of the layer, wind speed in the air gap is negligibly small. While the natural air circulation in the air layer cools the roof deck to some degrees, the main heat transfer in this layer is the emission and absorption at the deck surface and at the tile's underside [10, 11]. A numerical study has found that convective heat flux under a roof tile layer contributes about 0–0.284 W/m^2 to the ceiling [12], which is far lower than the heat entry through the roof to the building interior. The Nusselt number in the air gap is found at a range of 4–7,

(a) (b)

Figure 1: Concrete tiles are widely used as the overlay of a flat double-skin roof in Southern China. (a) A new concrete tile roof. (b) 2-3 years tile roof: the tiles have been darkened by dust deposit and algae growth.

further implying that convection inside the air layer is negligibly smaller than long-wave radiation [10].

As the heat transfer in the air layer is radiation-dominated, heat entry through the roof to the building interior would be cut down by modulating the emissivity of the deck and the tile's underside. Since the heat entry through the roof to the building interior is mainly controlled by the temperature at the roof deck, the following sections illustrate the influence of the emissivity of the roof deck and of the tile's underside on the heat absorption of the roof deck. A building cell is constructed with a flat double-skin roof, in which the outmost layer of the roof is housed for concrete tiles. The underside of each tile is coated with a specific paint to get a unique emissivity. Temperatures and heat fluxes at different heights are observed to confirm the influence of the emissivity of the tile's underside on the heat entry through the roof to the building interior.

2. Radiative Heat Transfer in the Air Layer

Sunlight absorbed at the rooftop heats up the tile and transfers the heat to the underside of the tile. Heat at the tile's underside propagates downward via convection, radiation, and conduction. According to Lai et al. [10], in the air gap, radiation is more significant than the convection and conduction. Photons emitting from the underside of the tile bounce back and force in the air layer until all photons are intercepted. At a double-skin roof with concrete tiles as the outmost layer, both the roof deck and the tile's underside can be treated as two parallel boundless gray sheets. Assuming that the emissivity and absorptance of both sheets do not vary with the temperature, net long-wave radiation absorbed by the roof deck, A_{nd} (W/m^2), ([13], pp. 495-496), is

$$A_{nd} = \frac{\sigma\left(T_b^4 - T_d^4\right)}{\left(1/\varepsilon_b\right) + \left(1/\varepsilon_d\right) - 1}, \quad (1)$$

where σ is the Stefan–Boltzmann constant ($=5.67 \times 10^{-8}$ $Wm^{-2} \cdot K^{-4}$); ε is the thermal emissivity; T(K) is the temperature; the subscript "b" represents the bottom (underside) of the tile; and the subscript "d" stands for the roof deck.

In summer months, the net radiation absorbed by the roof deck, to a great extent, controls the heat entry from the roof to the building. The heat entry can be cut down by reducing A_{nd}. According to equation (1), decreasing T_b can effectively reduce A_{nd}, which is a topic that has been studied elsewhere [9]. Increasing the temperature of the roof deck (T_d) drops A_{nd} but it would lead to more heat being conducted to the building interior. Decreasing the tile's bottom emissivity (ε_b), roof deck emissivity, and/or both could reduce the net long-wave radiation absorbed by the roof deck. A nonmetal roof deck has a typical emissivity of 0.70–0.95, so it is possible to decrease the emissivity of the roof deck by coating it with a low-emissivity paint. However, a roof deck is prone to deposit dust, which is equal to recoat the deck with a layer of nonmetal dust. As a result, it is impractical to decrease the emissivity of the roof deck. On the contrary, the tile's underside is free from dust deposit, so its emissivity could keep at a low value during its lifetime. Therefore, lowering ε_u would be the most retrofit strategy to cut down A_{nd}.

3. Experiments

Here, an experiment was conducted to confirm that the emissivity of the tile's underside controls heat entry through the roof to a building interior. The experiment simultaneously measured temperatures and heat fluxes of six roof tiles with the same albedo at the rooftop but with different emissivity values at the roof tile's underside. The roof tiles were assembled to a 1.8 m-height building cell with a $2.2 \times 2.2\,m^2$ double-skin roof, in which concrete tiles were the outmost layer (Figure 2(a)). The building wall was insulated, and the outmost skins of the walls were painted white. The rooftop of the building cell was constructed to six square modules with a $66\,cm \times 66\,cm \times 10\,cm$ (Figures 2(b)–2(d)), and each module was housed for a concrete roof tile, which was $66\,cm \times 66\,cm \times 2.5\,cm$. The thickness of the air gap beneath the tile was thus 7.5 cm (Figure 2(b)). According to the geometry of this double-skin roof, the projected area of each tile covers 95% view field of the center of the tile's bottom (computed as stated in [14]). This view factor means that the radiation transfer in the air layer can be deemed as one-dimensional.

The tiles were a Portland concrete type available in China markets. Using the test method of ASTM-E1461-13 [15] and

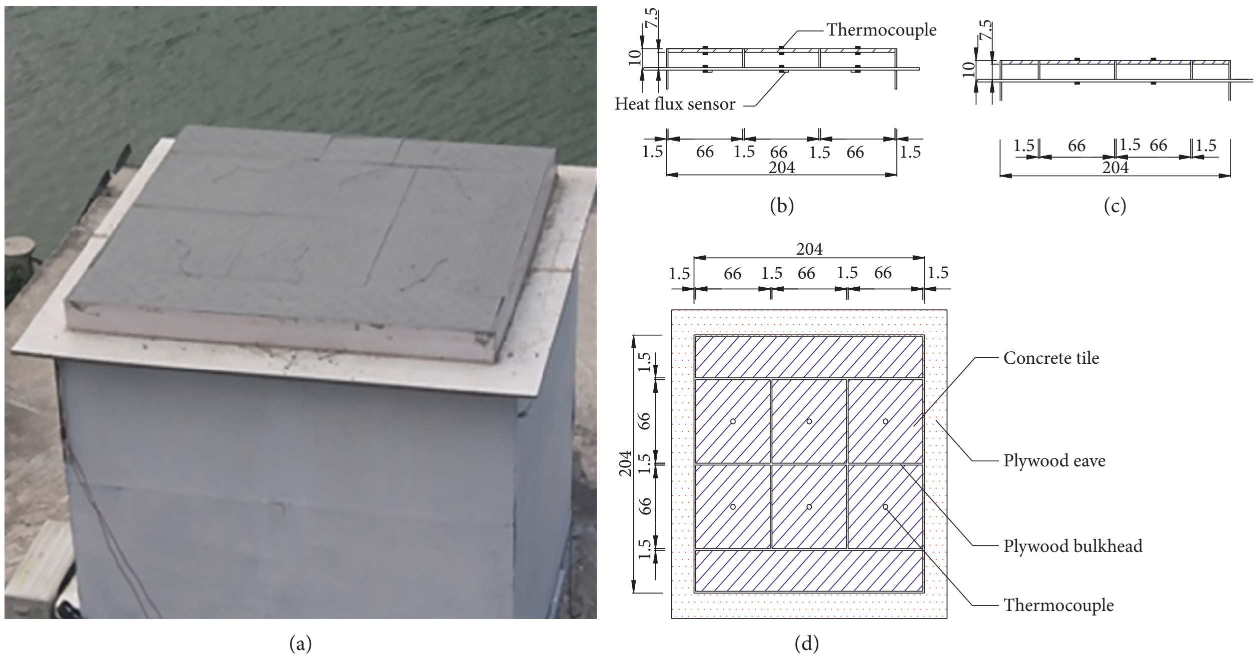

Figure 2: The experimental building cell and the deployment of measurement sensors on the concrete roof tile. (a) A photo of the roof, (b) roof's front view, (c) roof's side view, and (d) roof's plan view.

ASTM-C1470-06 [16], the thermal conductivity, heat capacity, and density of tiles were found to be 1.41 ± 0.03 W/m·K, 1020 ± 3, and $2405 + 10\ \mathrm{kg/m^3}$, respectively. Each tile's underside was coated with different emissivity values, which was achieved by mixing the white pigment, aluminum powder, and acetone in different fractions and then coating the tile's underside with the mixed latex. To get the real emissivity, a roof tile was cut to a suite of $5\ \mathrm{cm} \times 5\ \mathrm{cm} \times 1\ \mathrm{cm}$ samples, and each sample was then coated with a thin layer ($<10\ \mu$m) of the designed latex. The emissivity of the samples was measured under different temperatures. We found that when the concrete substrate was coated with about 10 micron latex, the emissivity of the coated sample (after the latex dried and hardened) was a constant, and the further addition of the latex to the substrate did not vary the emissivity. The estimated emissivity was also independent of the temperature in the range of interest (10–70°C in Figure 3). Their emissivity values were 0.32, 0.43, 0.54, 0.66, and 0.82, respectively, which were tested as stated in ISO 18434-1. These five tiles, together with a control tile without any coating on its bottom, were assembled into the designed six modules on the roof. The control tile had an emissivity of 0.93. The spacing between two modules was separated by a 1.5 cm thick plywood bulkhead, whose top was leveled with the rooftop to isolate the heat transfer in each module (Figure 2(b)).

Temperatures and heat fluxes were measured at different heights of the double-skin roof (Figure 4). For each tile, T-type thermocouples were attached to the rooftop, the tile's underside, roof deck, and the ceiling to log the local temperature. These four thermocouples were aligned vertically through the center of the tile (Figures 2(b)–2(d)). Each thermocouple was mounted to the upper side of a $1\ \mathrm{cm} \times 1\ \mathrm{cm}$ thin copper plate and was then calibrated in a thermostatic water bath. The underside of the copper plate

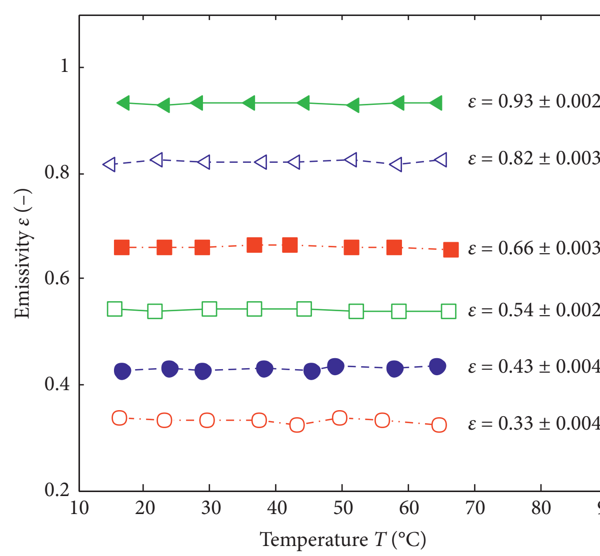

Figure 3: The emissivity of samples coated with different emission latexes. The emissivity is independent of temperature.

was coated with a thin layer of thermal grease (T-Global S606C thermal conductivity = 5.0 W/mK) and then attached to the thermocouple-located place. The corner of the plate was fastened by 502 Cyanoacrylate Adhesive Super Glue. At the underside of a specific tile, the thermocouple-mounted plate and the area surrounding were painted unicolor by the specific latex with a unique emissivity. After thermocouples were properly installed and tiles were completely assembled, the entire rooftop was painted unicolor, as indicated in Figure 2(a). The albedo of the rooftop was 0.269, which was measured according to the method proposed by Qin et al. [17].

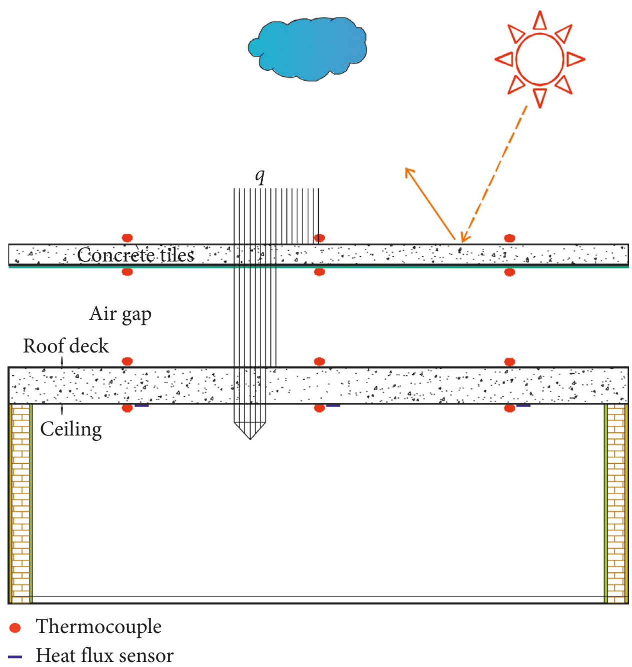

FIGURE 4: Sensors are deployed at different heights of a concrete tile roof to log the local temperature and heat flux.

In addition, on the ceiling and at 1.0 cm nearby the plate with thermocouples, a 1 cm × 1 cm × 0.5 mm heat flux sensor plate was attached. A thin layer of thermal grease was lubricated on the sensor-designed place, and then, the heat flux sensor was attached. Finally, the corner of the sensor was fastened by 502 Cyanoacrylate Adhesive Super Glue. In total, six heat flux sensors logged the heat entry through the roof to the building interior under the tiles with different emissivity values. The heat flux sensor, gSKIN®-XP, can read the heat flow signal with 3% error.

Both the temperature and heat flux were logged by a Compell CR3000 compliment, which logged 45 temperatures and 6 heat fluxes simultaneously. In addition, a weather tower (the Davis Instruments 6152) was installed at the same height with the rooftop to log the local weather information during the experiment. Observations began at the midnight of May 30, 2017 and ceased at the midnight of June 04, 2017, a time period that was rain free. The interior building cell was not air-conditioned during the experiment. The temperatures, heat fluxes, and weather data were logged at an interval of 5 minutes. Weather information during the experiment campaign can be referred to Figure 5.

4. Results

4.1. Emissivity of Tile's Underside Greatly Influences the Temperature of the Roof. The lowest emissivity in this experiment is $\varepsilon_b = 0.32$; and the greatest emissivity is 0.93, which is the emissivity of common concrete (the tile with $\varepsilon_b = 0.93$ is referred hereafter as the control tile). Temperatures at the top and underside of these two tiles indicate that the tile with $\varepsilon_b = 0.32$ stays hotter than the control tile (Figure 6(a)). The reason may be that a tile with low ε_b value impedes the heat of the tile propagating downward. At nighttime, a fraction of heat in the building cell discharges via the roof deck, which radiates the heat to the underside of the tile. As emissivity is equal to absorptivity, a tile with low ε_b value absorbs a small amount of heat and thus stays cool at nighttime (Figure 6(b)). While only observations of tiles with $\varepsilon_b = 0.32$ and $\varepsilon_b = 0.93$ are shown, the data for other tiles indicate the same trend. Therefore, the roof tile's temperature is controlled by the emissivity of the tile's underside.

The emissivity also dictates the temperature of the roof's deck (Figure 7). At nighttime, the difference is indistinguishable, possibly because in the air gap the nocturnal radiative heat transfer is far lower than the daytime one. During the daytime, the temperature of the roof deck under a tile increases with the emissivity of the tile's underside (Figure 7). This is because a tile with a larger emissivity radiates more heat to the underlying roof deck. It is also found that the daily maximum temperatures of the roof decks decrease linearly with the emissivity of the tile's underside, ε_b. Lowering ε_b from 0.93 to 0.32 decreases the maximum daily temperature of the roof deck about 3–8°C (Figure 8(a)). This temperature reduction caused by lowering the emissivity is greater than 2.4°C with the white cool coating [4] and 2–6°C when increasing the albedo of the roof deck up to 0.77 [9]. However, as shown in Figure 8(b), the daily minimum temperature of the roof deck seems unchanged in comparison with the daily maximum temperature. According to the daily maximum and minimum temperatures of the roof deck, it is concluded that the temperature amplitude of the roof deck decreases linearly with the emissivity of the tile's underside.

The temperature variation of the building ceiling is shown in Figure 9. The deck and the ceiling share a similar temperature pattern. But the ceiling temperature fluctuates less than the deck temperature because heat transfer attenuates with depth. Similarly, the daily maximum temperature of the ceiling increases linearly with the emissivity of the tile's bottom, but the daily minimum temperature of the ceiling varies indiscernibly (Figure 10). At noontime, the ceiling temperature under the control tile ($\varepsilon_b = 0.93$) is about 3-4°C greater than that under the tile with $\varepsilon_b = 0.32$. As the temperature at the ceiling is a surrogate of the heat entry through the roof to the building, it is concluded that lowering ε_b curtails heat entry.

4.2. Building Heat Gain/Loss (Q) Decreases Linearly with Tile's Underside Emissivity. A lower ceiling's temperature may indicate a less amount of heat (Q) entry to the building interior. The heat flux (q) observed at the ceiling fluctuates at a pattern similar to the temperature pattern at the ceiling (Figures 10 and 11). The fluxes below the five concrete tiles distinguish greatly, especially during the daytime, with a greater amount of heat inward to the building cell under a tile with a larger bottom's emissivity (one of the heat flux sensors damaged during the measurement). For instance, during a sunny day (June 03-June 04), the control tile leads to a maximum inward heat flux of 68 W/m^2 but the tile with a bottom emissivity of 0.32 leads to 42 W/m^2. During the night, the roof tiles with a greater bottom's emissivity

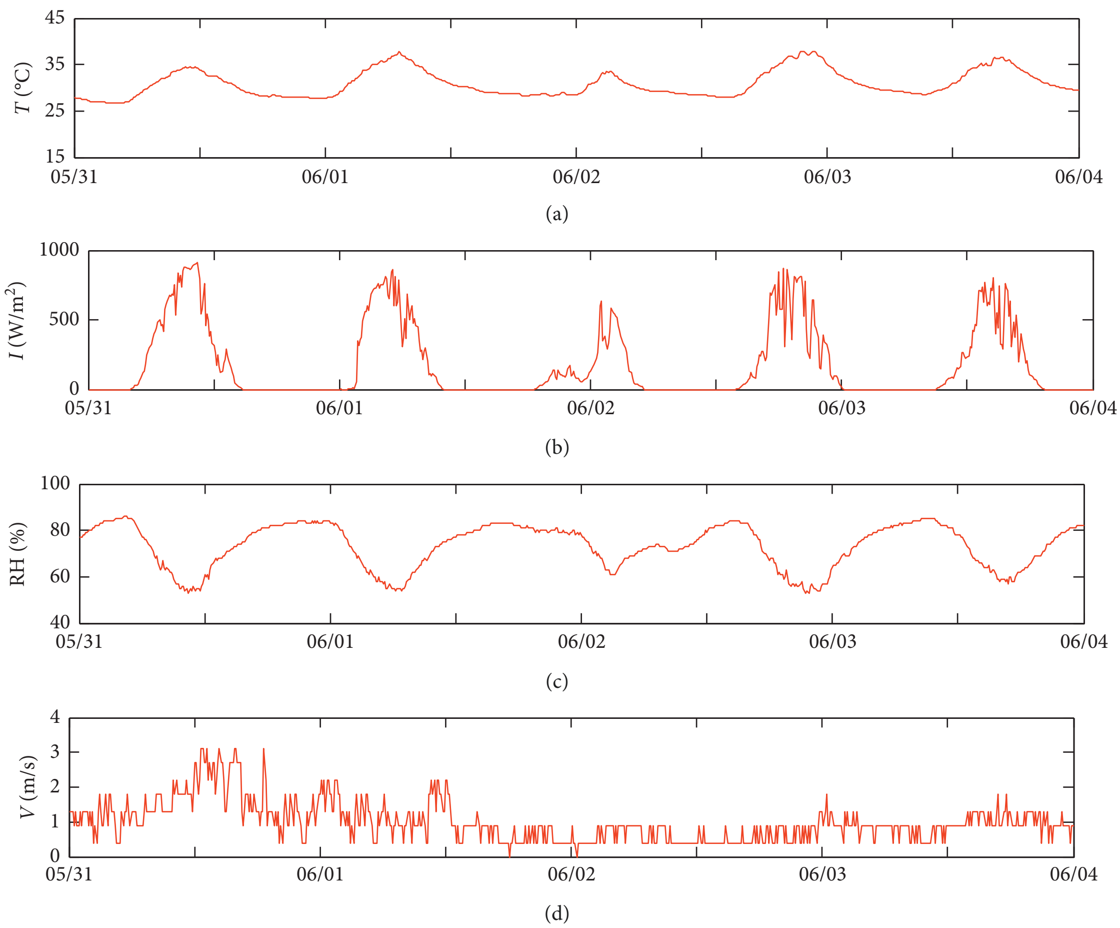

Figure 5: Weather data during the experiment: (a) air temperature, (b) global horizontal solar radiation, (c) relative humidity (RH), and (d) wind speed at 1.8 m height.

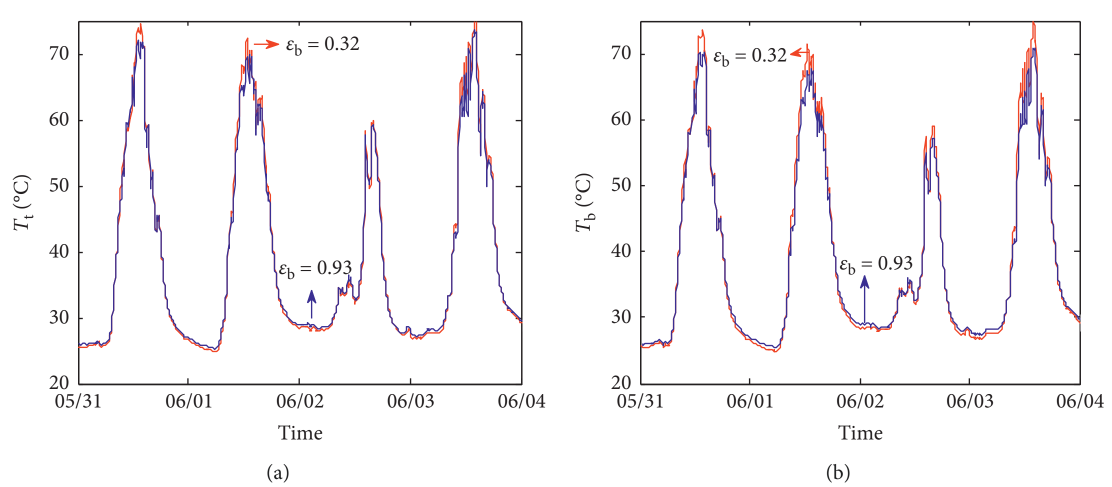

Figure 6: Tile's temperatures during the experiment: (a) rooftop temperature and (b) tile's underside temperature.

dissipate a larger amount of heat from the ceiling. The difference, however, is only 3–6 W/m^2.

In Figure 11, it is hard to distinguish the correlation between the heat flux (q) and the tile's bottom emissivity ε_b. We summate the daily heat inward/outward from the ceiling and then compare the summation with the tile bottom's emissivity. Only the data measured on May 31, June 01, and June 02 are shown for the avoidance of data congestion, but observations at other measurement days share similar correlations. The daily cumulative heat gain at the ceiling increases linearly with the tile bottom's emissivity ε_b (Figure 12(a)). The greater the ε_b value, the larger the

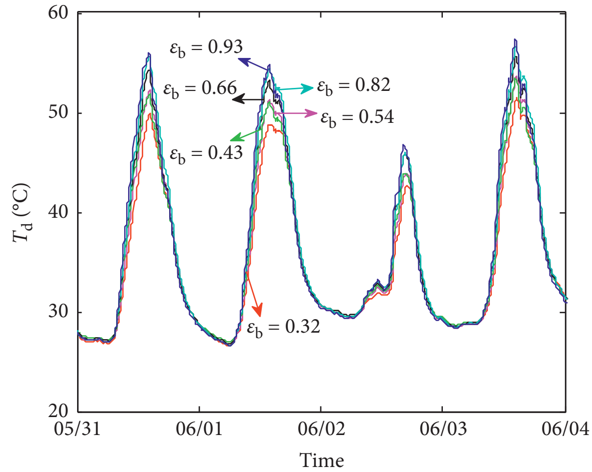

FIGURE 7: Temperatures of decks below the tiles with different ε_b values.

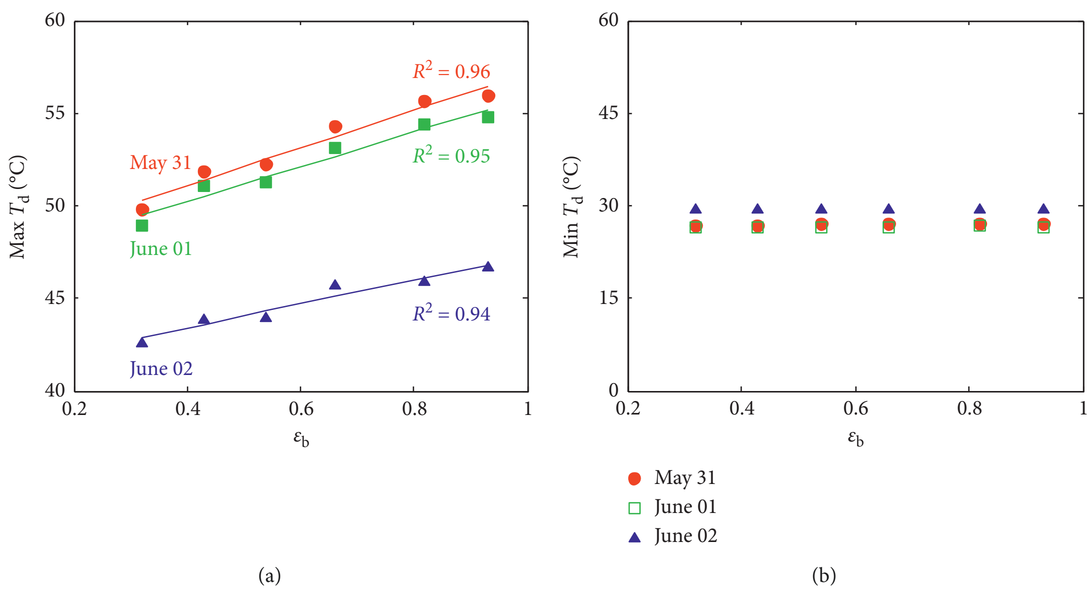

FIGURE 8: Daily maximum (max T_d) and minimum (min T_d) temperature at the roof deck: (a) max T_d and (b) min T_d.

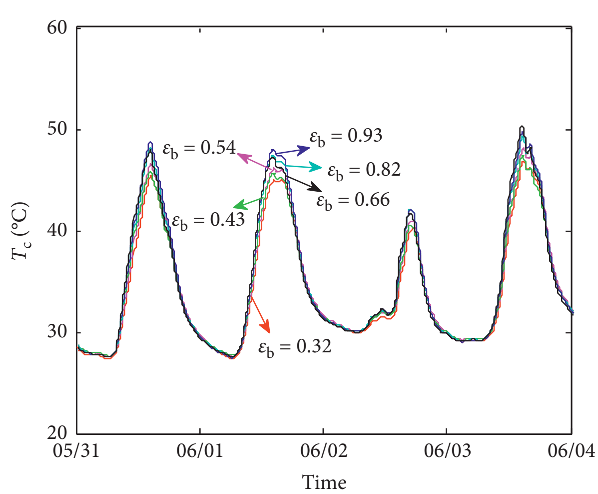

FIGURE 9: Temperatures of the ceilings under concrete roof tiles with different ε_b values.

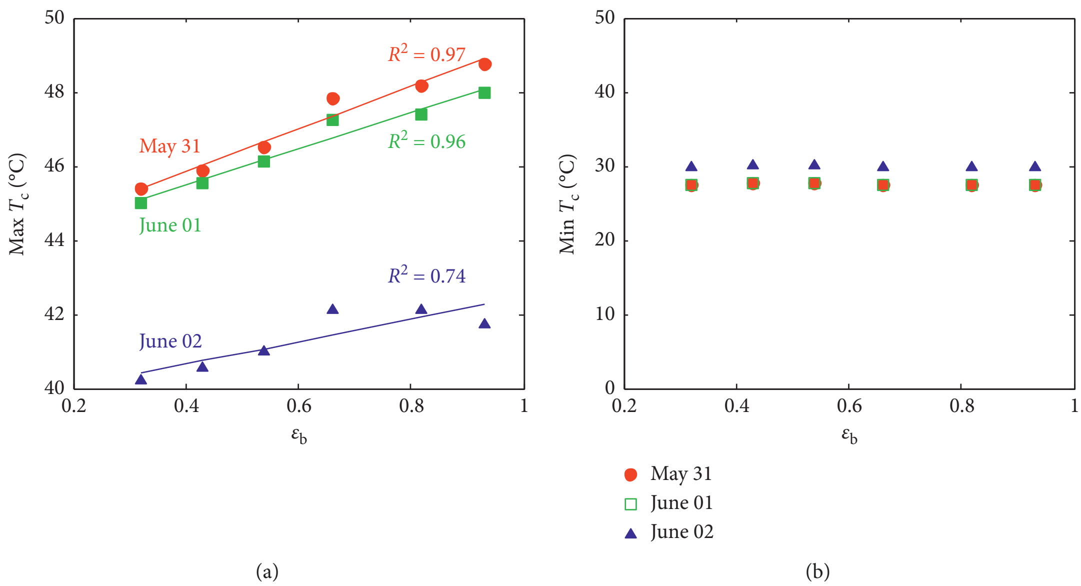

FIGURE 10: Daily maximum (max T_c) and minimum (min T_c) temperatures at the ceiling: (a) max T_c and (b) min T_c.

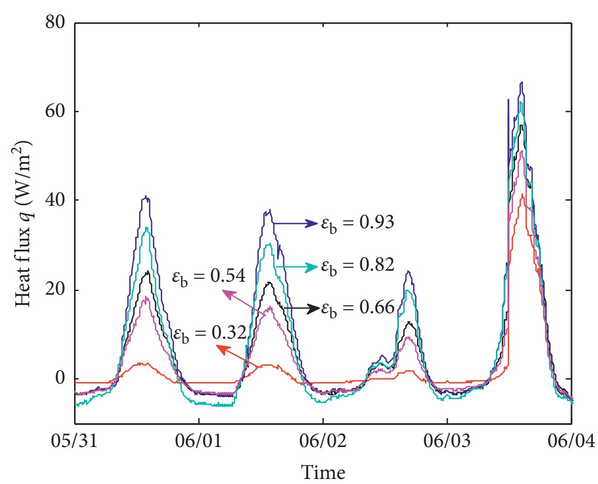

FIGURE 11: Heat fluxes at the ceiling are controlled by the tile's underside emissivity.

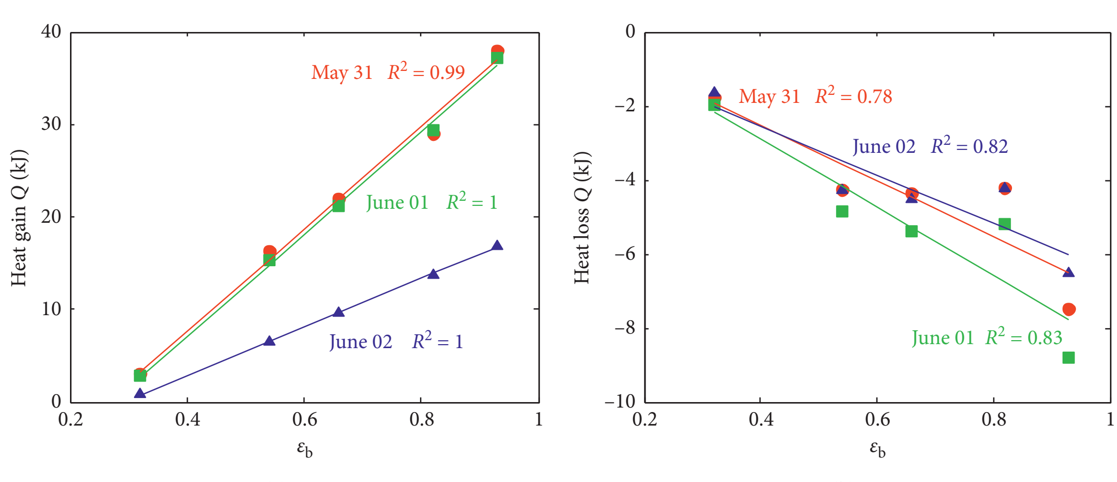

FIGURE 12: Daily cumulative heat gain/loss at the building ceiling varies linearly with emissivity: (a) heat gain versus ε_b and (b) heat loss versus ε_b.

amount of heat loss from the building ceiling (Figure 12(b)). The regression deviates somewhat from a linear correlation, possibly because the nighttime long-wave radiation in the air layer has the same order of the magnitude compared to the convection and conduction. In Figure 12, one can coarsely estimate that decreasing ε_b from 0.93 to 0.32 can curtail the heat entry to the building about 25 kJ/day, corresponding to 2.4 kW/hr/m^2 for the 0.66 m × 0.66 m tile (25/24/(0.66 ∗ 0.66) = 2.4). This heat loss is greater than those by increasing the albedo only in the existing studies, e.g., 0.21 kWh/m^2 from [4] and 234 W·hr/m^2 from [5]. While lowering the tile's underside emissivity linearly curtails the heat entry through the roof and also linearly impedes heat loss, the heat gain cutback far exceeds the heat loss reduction (Figure 12). Therefore, it is concluded that decreasing ε_b cuts down the heat entry through the roof to the building linearly.

5. Conclusions

To reduce heat entry from the roof during summer months, buildings in Southern China widely use a flat double-skin roof, in which concrete tiles are the outmost layer. In such a roof configuration, heat entry through the tiles to the building interior is greatly influenced by the emissivity (ε_b) at the bottom of the tile. To showcase this influence, this study built a flat double-skin roof with concrete tiles as the outmost layer and monitored temperatures and heat fluxes under tiles with different ε_b. The experiment confirmed that a concrete tile with a lower ε_b has a lower roof deck temperature and propagates the less amount of heat to the building interior, especially during the daytime. For instance, in our experimental campaign, decreasing ε_b of a concrete tile from 0.93 to 0.32 can reduce the heat entry through the roof to the building interior about 2.4 kW/hr/m^2 in average.

Appendix

The weather information during the experimental campaign is shown in Figure 5.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest related to this work.

Authors' Contributions

Xuejun Chen proposed the idea and wrote the paper; Yinghong Qin designed the experiments and supervised the research; Lei Wang and Zhikui Liu mainly conducted the experiments; and Ting Bao analyzed the experimental data and improved the paper. All the authors read and approved the final manuscript.

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